



AEP INTERSTATE PROJECT: WHY 765 KV AC?

I. Executive Summary

A modern, interstate transmission system is needed in the United States to meet growing electricity demands of the 21st century economy. In response to this need, American Electric Power (AEP) has proposed a major transmission project, dubbed the AEP Interstate Project [1], to allow efficient delivery of large blocks of competitively priced electricity while enhancing the grid reliability. The project is envisioned as a transmission backbone that will strengthen existing regional systems, from the Midwest to the eastern seaboard. It will feature the highest-capacity, proven power delivery facilities, aiming to launch a "transmission superhighway" system -- a vision modeled on President Eisenhower's national interstate highway plan.

In formulating the project, AEP carefully considered the available transmission technologies, including AC (alternating current), DC (direct current) and transmission voltage class. The guiding principle has been the project's goal to provide reliable transmission capacity and operating flexibility requisite of a competitive electricity marketplace.

Key physical and economic attributes of 765 kV and 500 kV transmission options are described in this paper. While the paper is focused on AEP's Interstate Project, the discussion is relevant to transmission infrastructure in general. It is shown that a 765 kV, 250-mile line, representative of each of the two segments comprising the AEP project, can carry substantially more power than a similarly situated 500 kV line. The load carrying ability, or loadability, of a double-circuit 500 kV line can approach that of a single-circuit 765 kV, but the resulting design would be a massive structure with the associated construction challenges, cost premium and visual impacts.

Experience indicates that transmission systems designed for 765 kV operation are inherently more reliable than those operating at lower voltage levels. With up to six conductors per phase, the 765 kV lines are virtually free of thermal overload risk, even under severe operating conditions. Moreover, outage statistics show that the 765 kV circuits, on average, experience significantly fewer forced outages than their 500 kV counterparts, with no multi-phase faults recorded at 765 kV in normal operation. These properties suggest a lower likelihood/severity of disruptions at 765 kV and an opportunity to apply effective remedies to further improve the line (and thus system) reliability.

Preliminary estimates place the AEP Interstate Project cost at approximately \$3 billion. Two-thirds of this amount is required for the construction of a 550-mile, 765 kV line the cost of which would rise by a factor of 1.4, to \$2.8 billion, if built as a double-circuit 500 kV alternative. The remainder represents line siting/certification/right-of-way (ROW) acquisition (about 20%) and station construction/equipment (10-15%) at the line terminals. Assuming no change in the ROW cost, the increased amount in combination with the ROW cost alone would exceed AEP's original cost estimate, even if none of the required station facilities were considered.

Since the project is in a conceptual phase, station costs are not yet well defined. Such costs include switchgear, transformation as well as shunt/series reactive compensation that might be required for local voltage support and/or loadability enhancement. With its higher loadability and greater reactive power capacity, significant cost advantages of the 765 kV transmission versus 500 kV are expected and will become still more apparent as the initial 765 kV "superhighway" evolves into an integrated network.

For these reasons, the 765 kV AC grid with ample capacity for future growth is considered the technology of choice for our nation's interstate transmission system.

II. Introduction

The power grid in the eastern U.S. today is characterized by mature, heavily-loaded transmission systems. Both thermal and voltage-related constraints affecting regional power deliveries have been well documented on systems operating at voltages up to, and including, 500 kV. While various mitigating measures are being proposed and/or implemented, they are largely incremental in scope and aimed at addressing specific, localized network constraints. Incremental measures are a tactical means of shoring up an existing system in the near-term. In the longer term, a mature system facing growing demands is most effectively strengthened by introducing a new, higher voltage class that can provide the transmission capacity and operating flexibility necessary to achieve the goal of a competitive electricity marketplace.

When a new voltage class is introduced on a transmission system, it may have the appearance of point-to-point transmission. Such was the case in 1969, when AEP energized the first 765 kV line between its Don Marquis and Baker stations, an initial step toward the present 2112-mile 765 kV network. It is also the case now, with the AEP Interstate Project, proposed as a link from AEP's 765 kV generating complex in West Virginia to Allegheny Power's Doubs 500 kV station in Maryland, to Public Service Electric & Gas' Deans 500 kV station in New Jersey. Accordingly, any comparison of transmission technologies for use in a particular project must recognize the project's goal, in addition to its physical and economic attributes.

Transmission technology choices considered for the AEP project include AC vs. DC and 765 kV vs. 500 kV. Higher voltages, up to 2000 kV, also received consideration based on AEP's prior research and successful testing, but they remain unproven in commercial operation. The attributes of these technologies -- transmission loadability, reliability, ROW requirements, line design and field construction challenges, visual impact and cost -- are discussed below in the context of the project's stated objectives.

III. AC vs. DC Transmission

Regional system requirements and available transmission technologies strongly influenced the conceptual design of the AEP Interstate Project [2]. From the outset, it became apparent that 60 Hz AC transmission technology, rather than DC, would be more suitable for use in this project.

AC would facilitate future additions of intermediate stations, a key advantage in populated areas such as the Midwest-East Coast region. These stations would act as exit and entrance ramps on an interstate highway, serving local load centers and/or providing outlets for new generation that may locate along the way. Moreover, the use of AC technology would enable expansion of the project into a high-capacity transmission grid overlaying the existing systems, with both readily integrated where so required. By contrast, traditional DC technology is generally limited in its application to point-to-point transmission traversing sparsely populated areas or where the systems being connected do not operate in synchronism.

A robust, integrated AC grid with ample capacity for future growth will provide a solid foundation for reliable service and ease of access to all users.

IV. Loadability

To assess the loadability of a high-voltage transmission line, planning engineers commonly use the concept of Surge Impedance Loading (SIL). SIL is a convenient “yardstick” for measuring relative loadabilities of lines operating at different nominal voltages. It has been shown that, when loadability is expressed in terms of SIL, a single curve, known as “St. Clair curve,” can be used to estimate the maximum permissible loading for a given line length [3]. Reflecting practical considerations and experience, the curve has been a valuable industry tool since its publication in 1953. It was subsequently supported with analytical methods and extended to voltages beyond then-highest 330 kV, at which system parameters play an increasingly important role [4].

The extended St. Clair curve is replicated in Figure 1. The curve is accompanied by a listing of common transmission line designs and associated SIL values found on the AEP System in the 1970s. Not listed in that figure is AEP’s latest 765 kV design with six-conductor phase bundles proposed for the Interstate Project.

Figure 1 is used to estimate loadability of a 250-mile line, representative of each of the two segments comprising the AEP project. Both 765 kV and 500 kV designs are examined. For 500 kV, two alternatives -- a single-circuit tower (SCT) and a double-circuit tower (DCT) -- are considered.

As shown, loadability of a 250-mile line is expected at about 1.2 SIL. For the proposed 765 kV line (SIL=2390 MW) this loading is 2800-2900 MW. The corresponding values for 500 kV SCT (SIL=880 MW) and 500 kV DCT (SIL=2x1000 MW), similar to those operating in the eastern U.S., are 1060 MW and 2400 MW, respectively.

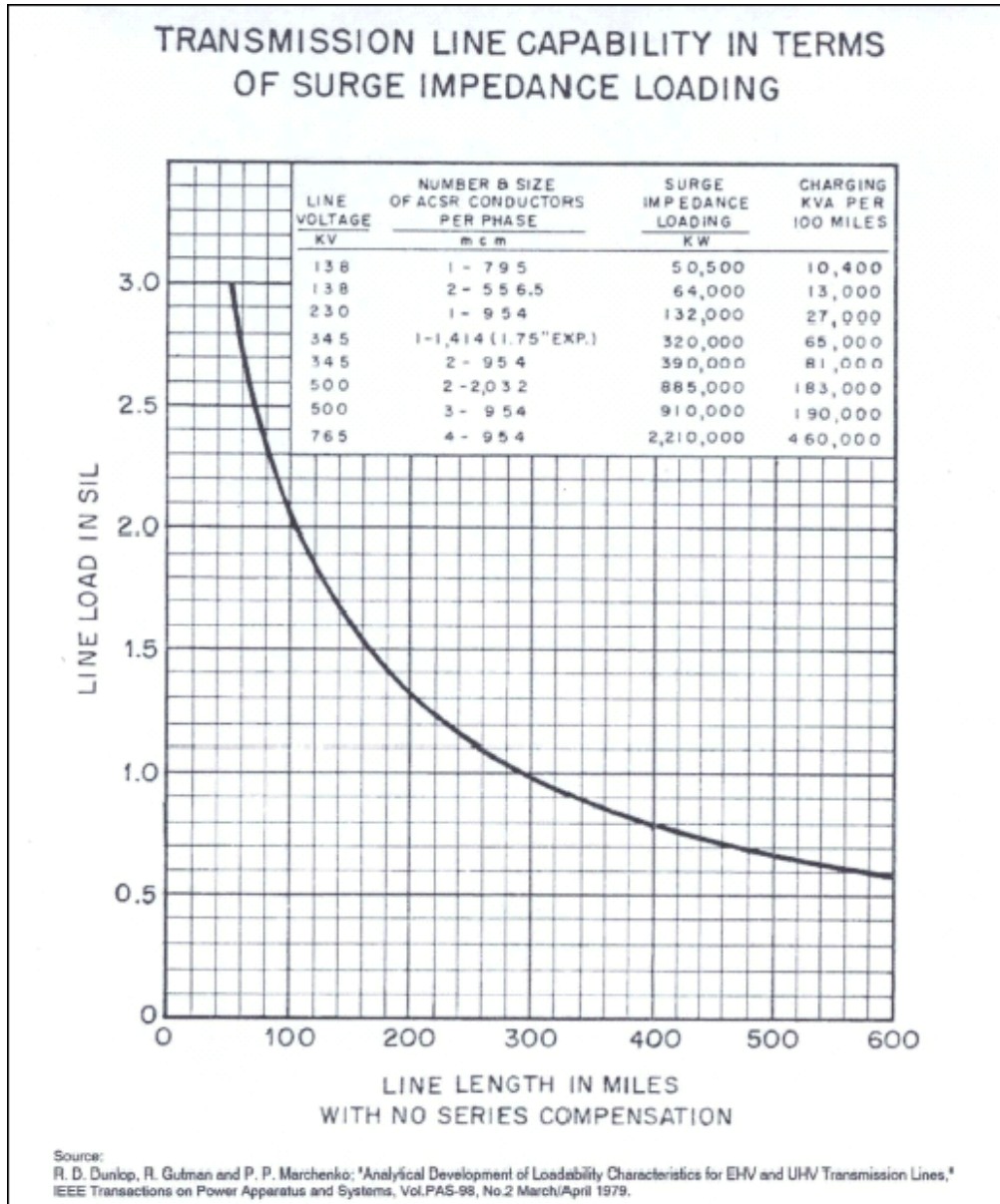


Figure 1. St. Clair Curve

The generalized line loadability characteristic in Figure 1 incorporates a set of assumptions with regard to system parameters and performance criteria. These assumptions reflect a well-developed system at each terminal of the line and operating criteria designed to promote system reliability. Clearly, a general transmission loading curve will not cover the entire range of possible applications. A customized version of the analysis underlying the loadability characteristic is summarized in Table 1 for the 765 kV and 500 kV alternatives noted above. This analysis centers on line loadability as limited by steady-state stability considerations, typically encountered in long distance transmission. Also, the analysis includes system terminations representative of those proposed in the AEP project.

As helpful as the loadability characteristic and simplified analyses are in providing estimates of the amount of power that can be transferred over a well-designed transmission system, they cannot be viewed as a substitute for detailed studies. Such studies are generally required to account for the actual structure of the network, including influence of voltage control sources, and to evaluate the system performance during contingency operation. Detailed studies are beyond the scope of this discussion.

Table 1. Loadability of 765 kV vs. 500 kV Transmission, 250 Miles (Steady-State Stability Limitation)

TRANSMISSION LINE	765 kV	500 kV SCT	500 kV DCT
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Phase Bundle	6-795 kCM ACSR	2-2049 kCM ACAR	3-1590 kCM ACSR
Conductor Diameter (in)	1.063	1.65	1.504
Conductor Weight (lb/ft)	0.896	1.90 (Est)	1.792
No. of Phase Bundles	3	3	6
Bundle Diameter (in)	30	18	20.8
Line Inductive Impedance*			
Per Mile (%)**	0.0087	0.0237	0.0105
250 Miles (%)**	2.17	5.92	2.62
Line Charging*			
Per Mile (Mvar)**	5.0	1.8	4.2
250 Miles (Mvar)**	1250	450	1050
Surge Impedance Loading, SIL (MW)	2390	880	2000
TERMINAL SYSTEMS			

Sending-End Terminal			
Strength (MVA)	45000	25000	25000
Eq. Reactance (%)**	0.22	0.40	0.40
Receiving-End Terminal			
Strength (MVA)	25000	25000	25000
Eq. Reactance (%)**	0.40	0.40	0.40
Transformation @ Receiving End			
1-765/500 kV, 2250 MVA			
Through Reactance (%)**	0.46		
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TOTAL REACTANCE (%)**	3.25	6.72	3.42
THEORETICAL LOADING LIMIT (MW)^	3080	1490	2920
PRACTICAL LOADING LIMIT (MW)^^	2770	1340	2630
	(1.2 SIL)	(1.5 SIL)	(1.3 SIL)

*Nominal values not adjusted for "long line" effect.
 **Expressed on 100 MVA and corresponding kV base. Total reactance includes line, terminal systems and transformation (if applicable).
 ^Maximum postulated loading assuming no stability margin (i.e., 90° angular displacement across line and terminal systems).
 ^^Loading limit with an assumed 10% stability margin and adequate voltage support provided by terminal systems.

It is apparent from Table 1 that a single 765 kV line, 250 miles long, can carry substantially more power than a similarly situated 500 kV line. A double-circuit 500 kV line can offer loadability approaching that of a single 765 kV line, but the resulting design would be a massive structure supporting twice the conductor weight of the 765 kV option, with the associated construction challenges, cost premium and visual impacts. Moreover, the 500 kV alternative(s) would merely “stretch” the capacity of the existing, mature 500 kV grid. Building 765 kV will launch a modern transmission superhighway system in the eastern U.S., helping to realize the promise of a 21st century electricity marketplace.

V. Reliability

A vibrant, reliable transmission system is essential to lowering the cost of electricity for all consumers. Experience shows that transmission systems designed for 765 kV operation are inherently more reliable than those operating at lower voltage levels.

The 765 kV lines are constructed using up to six conductors per phase to obtain acceptable corona and audible noise performance. Summer normal rating of a typical 765 kV line, including terminal equipment, exceeds 4000 MVA (conductors are rated still higher), virtually eliminating the risk of thermal overloads even under severe operating conditions.

Outage statistics [5] indicate that 765 kV circuits experience, on average, 1.0 forced outage per 100 mile-years. A comparable statistic for 500 kV is 1.4 forced outages per 100 mile-years. While single-phase faults are the dominant type of failures for both voltage classes, no multi-phase faults have been recorded at 765 kV in normal operation, short of tower failure. (AEP did experience 765 kV tower failures due to both severe icing and tornadoes.) This performance suggests a lower likelihood/severity of disruptions at 765 kV and an opportunity to apply effective mitigation measures, such as single-phase switching, to further improve the line (and thus system) reliability.

Single-phase switching (SPS) is a concept advanced and successfully first applied by AEP in the mid-1980s in conjunction with the Rockport Project in southern Indiana [6-7]. The concept has allowed integration of a major generating station with the system using only two 765 kV lines. SPS takes advantage of the superior outage performance of 765 kV lines by momentarily interrupting only one of three phases to clear temporary single-phase faults. This feature, made possible by the fact that all 765 kV-connected station equipment (circuit breakers, shunt reactors, etc.) are built as single-phase units, will enhance the proposed line's availability and minimize system disturbances caused by faults and associated switching operations.

The advantages of 765 kV become even more apparent when considering the 500 kV double-circuit alternative. With six distinct phase bundles, taller structures and lower ground clearances, the 500 kV DCT alternative would present an increased exposure to lightning strikes and tree contacts. Also, the use of large, heavy conductors at 500 kV would increase the risk of mechanical failures due to ice and wind loading. Moreover, any benefit to reliability that might accrue from having two circuits at 500 kV would simply vanish during heavy line loading, say 2500 MW, when an outage of one circuit would exceed the loading limit of the remaining circuit (refer to loadability discussion).

Reliability of the 765 kV system is, perhaps, best illustrated by the experience of August 14, 2003. On that day, a large segment of the interconnected grid in the eastern U.S. and Canada collapsed in a cascade that affected service to some 50 million people. It is notable that the cascade was effectively stopped at the “doorsteps” of AEP’s 765 kV transmission system.

VI. ROW Requirements

The width of rights-of-way necessary for transmission lines is dependent upon several factors. These factors include, but are not limited to, structure design, conductor blow-out conditions, future needs, topography, electric and magnetic fields, and static discharge considerations. Additional right-of-way or additional rights are sometimes obtained to increase reliability due to vegetation based issues.

AEP uses a minimum ROW width of 200 feet for its 765 kV construction. Typical industry ROW width for 500 kV is also 200 feet. AEP has used a 175 feet width for its nominal length of 500 kV infrastructure to interconnect with neighboring systems, but would consider 200 feet for future 500 kV designs. It is expected that a ROW 200 feet wide, and possibly wider, would be required to accommodate a 500 kV DCT line.

VII. Line Design and Construction

1. Structures and Foundations

To determine the optimal structure configuration for a given project, the topography, material lead times, available labor force and skill, and the material costs (namely steel) need to be evaluated. AEP has experience with several 765 kV tower types, including 4-legged lattice structures, guyed vee towers and tubular pole-type structures (Figure 2). During the nearly four decades of building 765 kV lines, AEP has been very successful in matching these different structure types with the various terrain and land uses encountered in the multi-state service area.

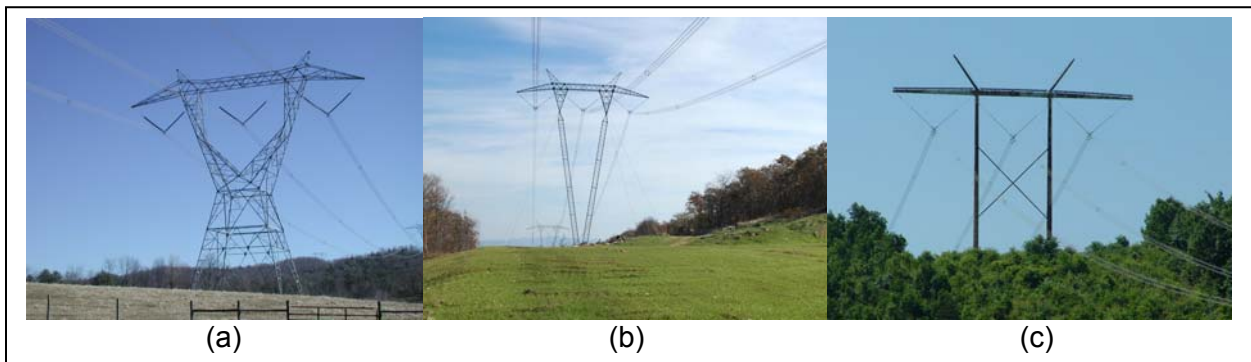


Figure 2. Typical 765 kV Transmission Structures on AEP System

(a) 4-legged lattice steel self-supporting tower; (b) Guyed vee lattice steel tower;
(c) Tubular steel structure

AEP has made extensive use of self-supporting and guyed vee structures for 765 kV lattice construction. Also, AEP designed and installed several tubular steel H-Frame type structures for use at 765 kV. For 500 kV DCT, AEP would utilize a tubular design of either H-Frame, three-pole or delta configuration. Lattice structures are generally lighter than tubular pole designs as the lattice design places material where needed. Tubular poles, which place material where not needed, use a regular, solid polygon to take advantage of fabrication and welding technology. Another advantage in tubular is the much faster design, detailing and fabrication process. Since tubular design has high performance predictability, full scale tests may be avoided. New and competitive lattice designs require testing to prove out the complex detailing.

Tubular assembly and erection is relatively simple using low labor hours but expensive, heavy equipment. There is a definite time advantage but not necessarily a cost advantage. Lattice assembly and erection is more complex. However, because lattice designs are generally lighter than tubular designs, and the fact that construction contractors generally charge by the pound, construction savings on large projects using lattice is possible. Once lattice tower designs are proven, the tower series are reused in future project designs greatly reducing the testing costs.

Foundations are more difficult to assess. Lattice construction is far superior to tubular in mountainous or more difficult terrain. The lattice foundation is designed to be constructed in such terrain. Tubular foundations are generally poured on the structure location as reinforced concrete piers. This relates to a large advantage for tubular poles in areas accessible to concrete batch plants and good road access in the flatter terrain.

Tubular success versus lattice is easily achievable in areas of this type when local contractors are set up for concrete work. The critical factor needed is a tubular design optimized on structure and foundation costs. This can be achieved with thorough attention to preemptive subsurface soil investigations and geologist/foundation engineer reports prior to commencing design.

Assuming that a 500 kV DCT design using three-conductor bundles (Lapwing, 1590 kCM ACSR) can deliver comparable power to a single circuit 765 kV with six-conductor bundles (Tern, 795 kCM ACSR), a comparison of the various structures needed to support each delivery system is presented below.

2. Conductor Wind and Weight Loading

A basic comparison of a tubular steel option for 765 kV and double circuit 500 kV shows that the latter would be considerably heavier and would have increased wind loadings. This comparison is summarized for the assumed 1300-ft horizontal and 2000-ft vertical spans, and 25 lb/ft² wind.

Table 2. Conductor Wind and Weight Loading

	765 kV -----	500 kV DCT -----
Conductor Type	795 kCM ACSR (Tern)	1590 kCM ACSR (Lapwing)
Conductor Diameter (in)	1.063	1.504
Conductor Weight (lb/ft)	0.896	1.792
No. of Conductors/Phase Bundle	6	3
No. of Phase Bundles	3	6
Transverse Wind Load (lb)*	51,821	73,320
Vertical Weight Load (lb)**	32,256	64,512
Lapwing/Tern Wind Load Ratio		1.41
Lapwing/Tern Weight Load Ratio		2.00

*Assuming 1300-ft horizontal span and 25 lb/ft² wind (Load = Cond. diameter x #Cond./phase x #Phases x 1300 ft x 25 lb/ft²).

**Assuming 2000-ft vertical span (Load = Cond. weight x #Cond./phase x #Phases x 2000 ft).

As shown in Table 2, one can expect the 765 kV single-circuit structure to be shorter over the same terrain for the same design criteria and have much less wind load and vertical load. This means smaller structures and foundations, in both dimensions and weight.

In addition to the obvious aesthetic benefit of the single-circuit design, it also provides a cost savings directly proportional to the steel structure weights. The estimated weight savings is approximately equal to the cube root of the above wind and weight load ratios, as this is proportional to section modulus of a regular polygon.

$$\text{Pole weights and foundation size} = \sqrt[3]{1.41} = 1.12.$$

$$\text{Arm weights and horizontal bridge weight} = \sqrt[3]{2.00} = 1.26.$$

Contractor construction equipment and labor costs would approximate these values for Pole Assembly/Erection and Foundation Installation. This is inexact as contractors generally base the labor and equipment costs on structure total weights. Foundations are generally priced by volume of rock or soil removed and discarded together with volume of concrete installed. Foundations in tubular design are controlled by overturning moment; this is proportional to the transverse loading.

VIII. Visual Impact

1. Visibility

Apart from the line design and construction considerations, the larger conductor used in a 500 kV double-circuit delivery system would have approximately 1.4 times the visible surface area of an electrically equivalent single circuit 765 kV. Also, the former would require taller structures to maintain ground clearances. This means that more “material” would be in the air and thus highly visible. Both of these attributes tend to decrease the

aesthetic value of a double-circuit line. This comparison is illustrated for selected examples of tubular steel designs (Figure 3) as well as lattice tower designs (Figure 4).

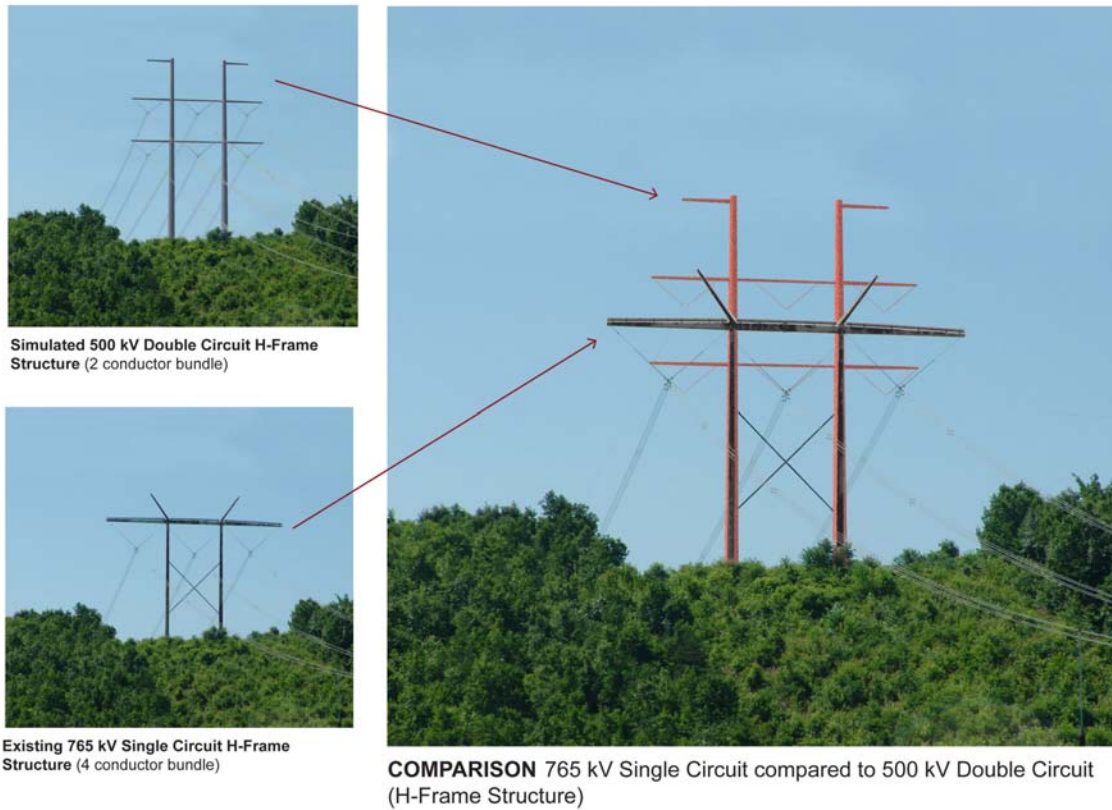


Figure 3. Simulated Comparison of Tubular Structures – 500 kV Double Circuit and 765 kV Single Circuit

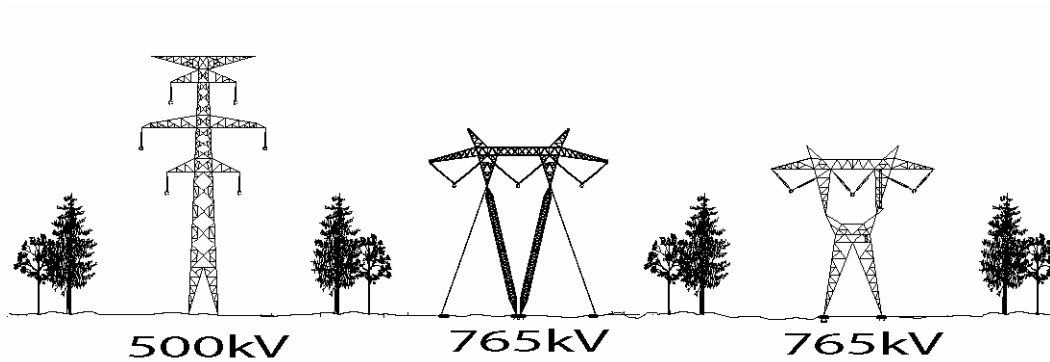


Figure 4. Comparison of 500 kV Double Circuit and 765 kV Single Circuit Lattice Structures

2. Visual Studies

For either option, steps can be taken to lessen the visible impact of the structures and associated conductors. When locating the ROW, AEP conducts visual studies at critical locations and develops simulations of the landscape after the line is constructed [8]. Figure 5 exemplifies these visual studies with the “before” and “after” construction photos. These photos demonstrate AEP’s care and attention to detail in striving to achieve a realistic representation of the final ROW location.

As the line location is finalized, AEP complies with all applicable federal statutes and regulations including the National Environmental Policy Act (NEPA), National Historic Preservation Act, and Endangered Species Act. AEP also complies with all applicable state and local statutes and regulations, adheres to all conditions stipulated by each state public utility commission having jurisdiction over the project, and cooperates with other interested state environmental agencies.

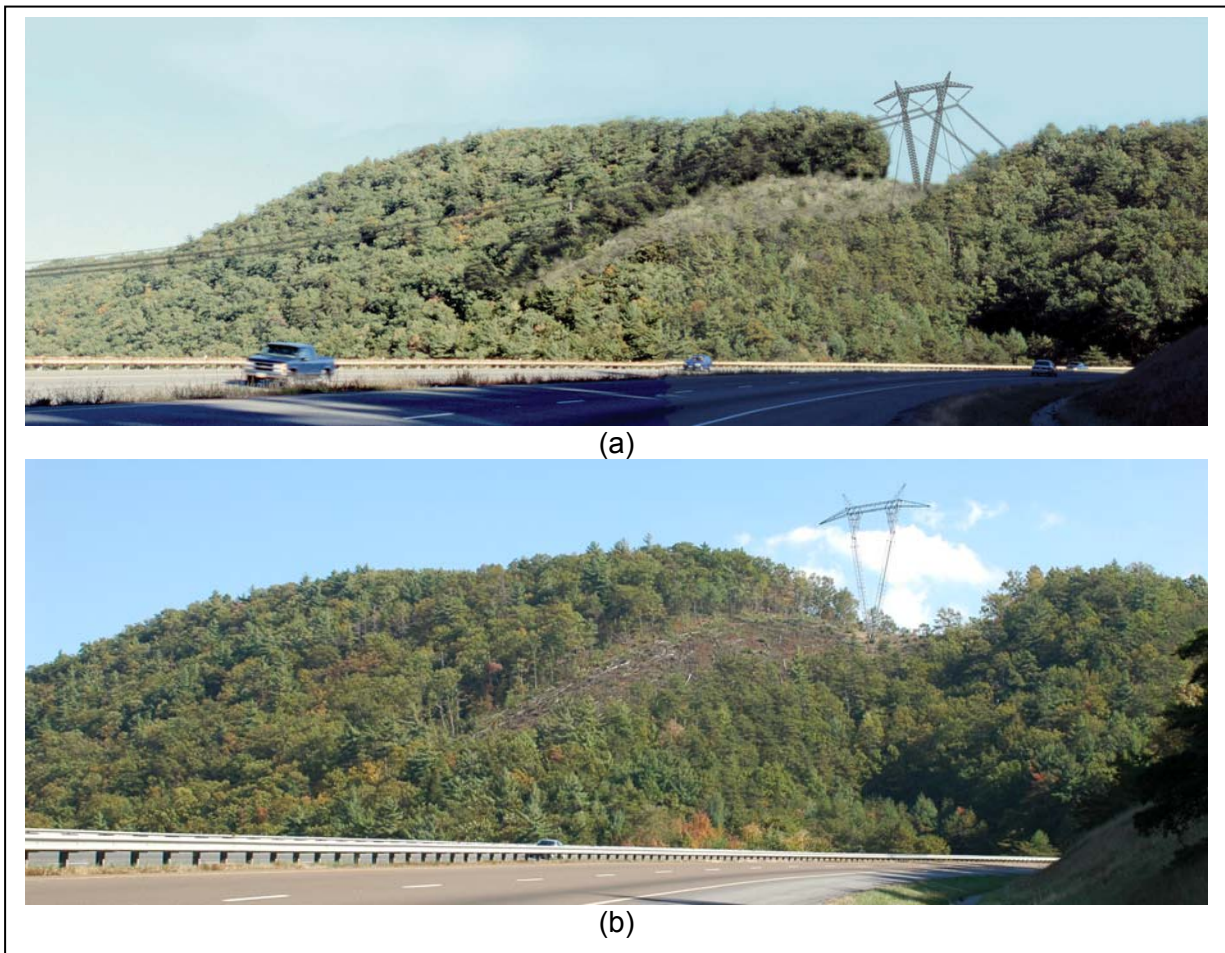


Figure 5. Visual Simulation

(a) Visual simulation of a 765 kV tower within the view shed of Interstate 77, five years before construction; (b) Actual tower during construction without conductor (wire).

Once the ROW and tower locations are finalized, AEP considers various mitigation techniques that can help reduce the impact of the project on the immediate area. For example, in the past, AEP has successfully conducted site-specific studies with geology experts to avoid or minimize any potential impact on the groundwater supply; relocated an Appalachian Trail shelter to mitigate the visual impact to the shelter and its users; established wildlife feed patches within the ROW on private lands to foster wildlife habitats; identified flyways for raptors (such as hawks and eagles) and successfully installed bird diverters on the wires of the power line to help prevent birds from striking the line.

3. Darkened/Low Reflective Materials

Unlike electrical transmission lines built 50 years ago, AEP's most recent lines have been successfully blended in with the landscape by careful siting of the ROW and by using darkened or low-reflective materials (Figure 6). These enhancements have proven to be of significant value in mitigating the visual impact of transmission lines.

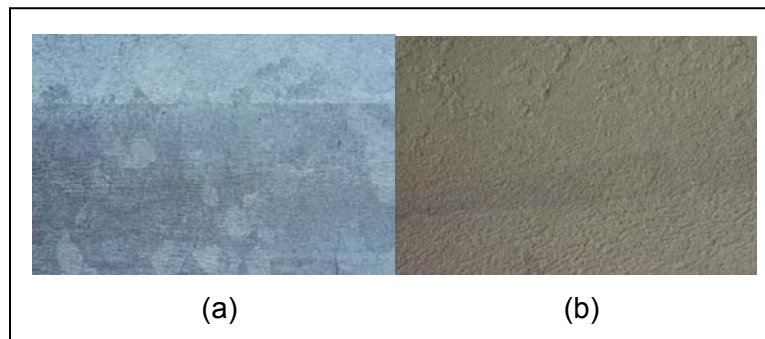


Figure 6. Surface Treatments for Tower Steel

(a) Typical galvanized; (b) Darkened steel

The darkened effect is achieved by various treatments to the material surface during the fabrication process. Use of these materials results in a project where the towers and wires blend in very well with a rural landscape as demonstrated in Figure 7 and

Figure 8.

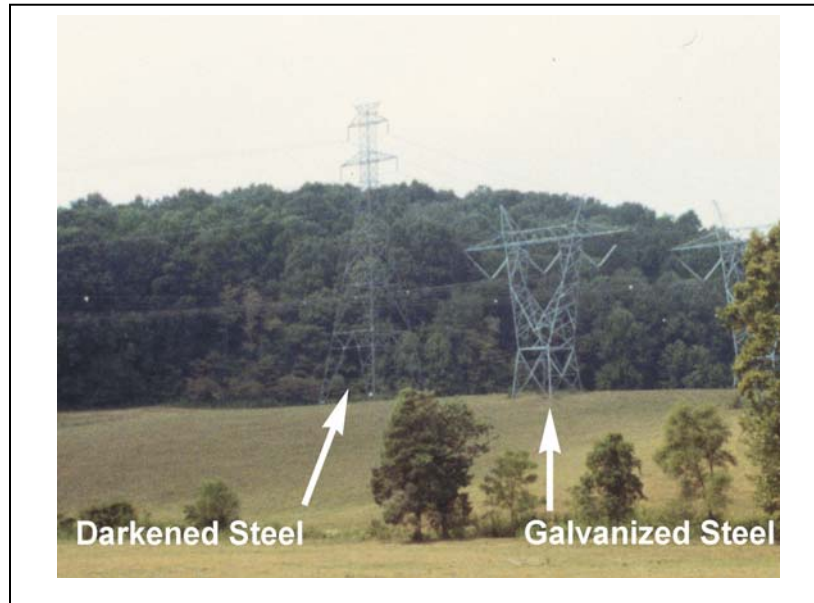


Figure 7. Comparison of Galvanized and Darkened Steel on Transmission Towers



Figure 8. Darkened Steel Transmission Towers Before Wire is Installed

IX. Cost

Additional material and steel weights of the 500 kV double circuit would tend to increase cost by a factor of 1.4 over an electrically equivalent 765 kV single-circuit option.

Although the number of conductor-miles is the same for each alternative, the fact that Lapwing conductor (1590 kCM ACSR) cost on a per-foot basis is approximately twice that of Tern (795 kCM ACSR) would increase the overall project cost for the 500 kV double-circuit option. Additional conductor hardware and insulators also would be needed. Furthermore, double-circuit installations increase the amount of conductor pulling, sagging and clip-in operations needed, directly affecting the construction time and labor.

Structure weights also would be greater for the 500 kV double-circuit option. Since steel is purchased mainly by weight, the 1.1 times additional weight needed for the double-circuit option would increase structure costs by an equivalent ratio. This also equates to a construction premium as most contractors estimate and bill on steel weights.

For the AEP Interstate Project, as proposed, the cost of 765 kV line construction (including material) is estimated to account for about two-thirds of the \$3 billion total project cost. The remainder represents line siting/certification/ROW acquisition (20%) and station construction/equipment (10-15%). If the 500 kV double-circuit alternative were selected, the line construction cost would increase by a factor of 1.4, to \$2.8 billion. Assuming no change in the ROW cost, this amount in combination with the ROW cost alone would exceed by a significant margin AEP's original cost estimate, even if none of the required station facilities were included in the 500 kV project scope.

X. Conclusion

AEP believes that 765 kV transmission offers significant performance and cost advantages over the competing technologies for use in the proposed Interstate Project (or other projects of similar scale). The advantages of 765 kV are even more compelling in light of the project's stated objective -- to launch a modern transmission superhighway system befitting the U.S. economy needs in the 21st century.

XI. References

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